91602
new 82-10

COMPLIMENTARY COPY
Please Credit Ontario Hydro Research if Reproduced in Whole or in Part

LEGAL NOTICE

This report was prepared by Ontario Hydro and, while effort has been made to assure the accuracy and applicability of the material contained herein, neither Ontario Hydro nor any person acting on its behalf:

(a) makes any warranty, express or implied with respect to the use of any information, apparatus, method or process disclosed in this report or that such use may not infringe privately owned rights; or

(b) assumes any liabilities with respect to the use of, or for damages resulting from the use of, any information, apparatus, method or process disclosed in this report.

ontario hydro research division

LIFT TRUCK BATTERY CHARGER EFFICIENCY

90-339-K
C.E. Keyes
Utilization Engineer
Utilization Section
Electrical Research Department

Abstract

A program to promote off-peak charging of lift truck batteries raised a number of concerns regarding the effect of rigid charging schedules on battery temperature. This report addresses these concerns as well as others including charging efficiency, demand profiles and power quality issues. A total of eight chargers from representative manufacturers and two battery types (3 batteries) were used in the test program.

Based on the test results, it was concluded that operations employing one battery per lift truck charged once daily would not experience adverse temperature effects from off-peak charging. This was attributed to the large battery thermal mass which did not cool down significantly four hours after charging. The difference in the final core temperature after discharging the battery was found to be very small.

Charger efficiency ranged between 80.2% and 89%. **Switch-mode** (High-Frequency) chargers were the most efficient followed by **Magnetic-Amplifier** (Mag Amp or Saturable-Reactor), **Thyristor** (SCR) and **Ferroresonant** (Constant-Voltage) types.

In terms of power quality, the Ferroresonant chargers had the lowest measured waveform distortion.

job	file	date	report no.
12-226	814.3	January 22, 1991	90-339-K

91-07168/

Table of Contents

		Page
1	Introduction	1
2	Approach	2
3	Results	4
	3.1 Temperature	5
	3.2 Power Factor	9
	3.3 Charger Efficiency	11
	3.4 Demand	14
	3.5 Amp-hour Charging and Discharging Profiles	16
4	Discussion	19
5	Conclusions and Recommendations	21
6	Acknowledgements	22
APPENDIX		23

List of Figures

		Page
Figure 1	Probe Detail	2
Figure 2	Thermocouple Locations	3
	Cell Temperature During Charge	7
Figure 3	Charger 1	7
Figure 4	Charger 2	7
Figure 5	Charger 3	7
Figure 6	Charger 4	7
Figure 7	Charger 5	7
Figure 8	Charger 6	7
Figure 9	Charger 7	7
Figure 10	Charger 8	7
Figure 11	Battery Temperature Decay	8
	Power Factor	10
Figure 12	Charger 1	10
Figure 13	Charger 2	10
Figure 14	Charger 3	10
Figure 15	Charger 4	10
Figure 16	Charger 5	10
Figure 17	Charger 6	10
Figure 18	Charger 7	10
Figure 19	Charger 8	10
	Charger Efficiency	13
Figure 20	Charger 1	13
Figure 21	Charger 2	13
Figure 22	Charger 3	13
Figure 23	Charger 4	13
Figure 24	Charger 5	13
Figure 25	Charger 6	13
Figure 26	Charger 7	13
Figure 27	Charger 8	13

Demand 15
Figure 28 Charger 1 15
Figure 29 Charger 2 15
Figure 30 Charger 3 15
Figure 31 Charger 4 15
Figure 32 Charger 5 15
Figure 33 Charger 6 15
Figure 34 Charger 7 15
Figure 35 Charger 8 15
Amp Hours 17
Figure 36 Charger 1 17
Figure 37 Charger 2 17
Figure 38 Charger 3 17
Figure 39 Charger 4 17
Figure 40 Charger 5 17
Figure 41 Charger 6 17
Figure 42 Charger 7 17
Figure 43 Charger 8 17

Appendix

Figure A-1 Equipment and Wiring Schematic 24
Figure A-2 Detail of Safety Shut-Off System 25
Figure A-3 Examples of Chargers Tested 26
Figure A-4 Batteries Tested 27

List of Tables

Page

Table I Lift Truck Battery Chargers Tested 2
Table II Charging Temperature Rise 5
Table III AC - DC Charger Efficiency (Average) 11
Table IV Charge / Discharge Efficiencies 12

ontario hydro
research division

To
TO: Mr. J.E. Mitchell
Manager
Technical Services and Development
Program Support and Services Division

LIFT TRUCK BATTERY CHARGER EFFICIENCY

C.E. Keyes

1 Introduction

The main objectives of this project were to evaluate battery charger efficiency and to investigate the effect of charge cycles on battery core temperature rise. As well, the relationship between battery core and case temperature was determined. The power quality of each charger was monitored and compared in relative terms.

The temperature information was used to ascertain the practicality and safety of advocating off-peak charging of lift truck batteries between 11:00 PM and 7:00 AM. Off-peak charging could reduce the Ontario Hydro peak demand by up to 18 MW[1].

This report summarizes the charge cycle test results of eight lift truck battery chargers evaluated on three, 720 A.h batteries. The eight chargers were representative of chargers found in today's marketplace. They included **Switch-mode** (High-Frequency), **Magnetic-Amplifier** (Mag Amp or Saturable-Reactor), **Thyristor** (SCR) and **Ferroresonant** (Constant-Voltage) types. Two common battery types were used: **Flat Plate** and **Tubular Plate**.

Harmonic measurement results are noted in this report. The topic is covered in greater detail in Ontario Hydro Research Reports 90-47-H "*Harmonic Currents for Industrial Battery Chargers*" (chargers 1-4) and 90-324-K "*Harmonic Currents From Industrial Battery Chargers - Addendum*" (chargers 5-8 plus overview of chargers 1-8). Both reports were prepared by G.K. Hatanaka.

All tests were conducted in the laboratory under controlled conditions. The results are displayed in graphical measured value versus time format. Each parameter is presented for all chargers on a single page to facilitate comparison.

---

[1] T.J. Parker, Program Management, Ontario Hydro

2 Approach

Eight representative samples of 600 V, 3ø chargers (Table I) were tested under laboratory conditions on two 48 V, 720 ampere-hour (A.h) **Flat Plate** batteries and one equally rated **Tubular Plate** battery. Thermocouples were inserted into the battery through the cell vent caps using thin glass wells. See Figure 1 for details of the probe used to monitor cell electrolyte temperatures. Case temperature was monitored at several locations (see Figure 2, page 3). Room ambient temperature was recorded during testing. For these tests, temperature rise is defined as the maximum temperature change in degrees celsius from the beginning to the end of each test.

A dummy load, specifically designed for determining battery capacity, was used to discharge the batteries using the standard 6-hour discharge rate[2] (C/6[3], 120A for a 720 A.h battery).

Table I Lift Truck Battery Chargers Tested

Ch. #	Type
1	Thyristor (SCR)
2	Magnetic-Amplifier (Saturable Reactor)
3	Ferroresonant (Constant-Voltage)
4	Switch-Mode
5	Magnetic-Amplifier
6	Ferroresonant
7	Ferroresonant
8	Magnetic-Amplifier

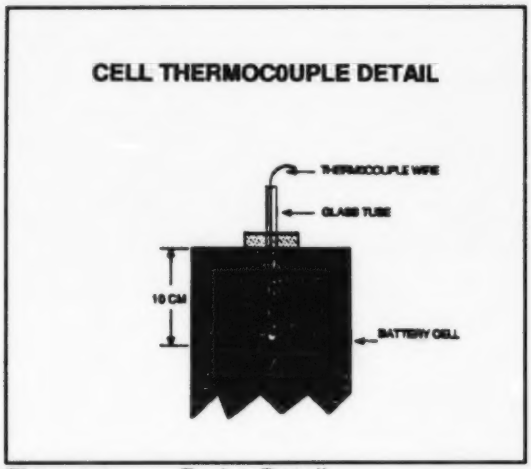

Figure 1 Probe Detail

Other instrumentation included measurement of the ac real and reactive power during charging, and dc current and voltage during both charging and discharging.

The test was set up to permit concurrent charging and discharging of the two batteries.

---

[2] NEMA Standard IB 2-1987 *"Determination of Capacity of Lead-Acid Industrial Storage Batteries for Motive Power Service"*.

[3] Discharge Rate C/h where:
C = Battery Rating in A.h, and
h = time in hours

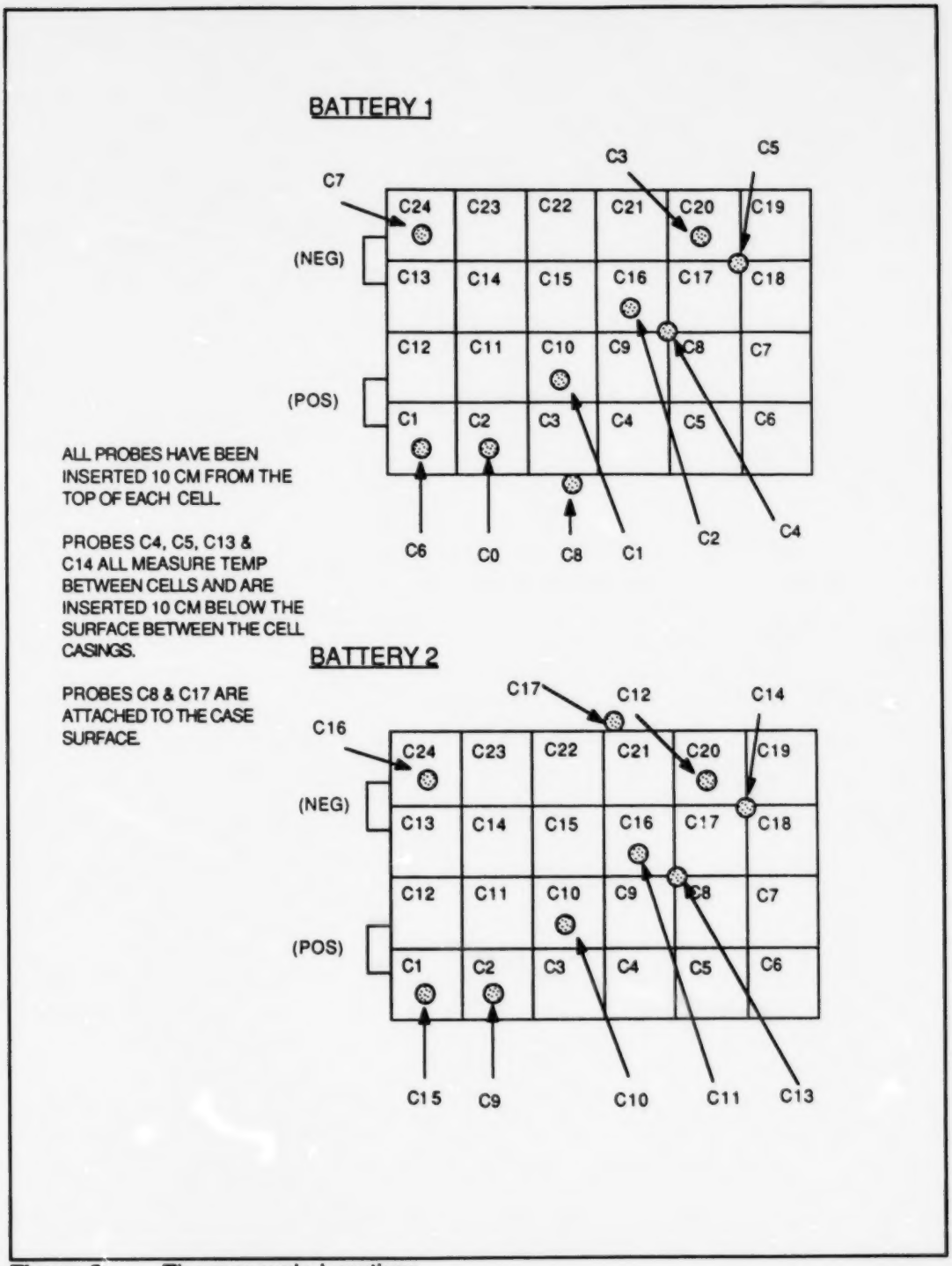

Figure 2 Thermocouple Locations

Four basic tests were used:

"Hot Charge" -	charging the battery immediately after discharging down to 1.72 V per cell at the 6-hour discharge rate.
"Cold charge" -	charging the battery after allowing the battery to rest at least 3-4 hours in accordance with the recommendations of many battery manufacturers.
"Hot discharge" -	discharging the battery immediately after charging.
"Cold discharge" -	discharging the battery after allowing the battery to cool at least 3-4 hours in accordance with the recommendations of many battery manufacturers.

Since the three batteries were new, a "break-in" period was required before efficiency measurements were taken. New lead-acid storage batteries require about 6 -10 charge cycles to reach full capacity. During this stage, harmonic (power quality) measurements were taken.

Once the break-in period had been achieved, all of the basic tests were performed using each charger on two batteries. This was necessary so that efficiencies could be determined for each charger under different operating conditions.

One additional set of discharge tests was performed using one of the chargers to study the effect of increased temperature rise when the 6-hour discharge rate (C/6, 120 A) was doubled (C/3, 240 A).

3 Results

Graphs, depicting typical test data for all chargers versus time, have been printed on individual pages to facilitate comparison (Temperature, page 7, Power Factor, page 10, Charger Efficiency, page 13, Demand, page 15, and Amp Hours, page 17). All have a 7-hour time axis with the exception of Chargers 2 and 8 (10-hour axis) which required more than 9 hours to fully charge the battery.

3.1 Temperature

Temperature rise was measured at several points in the battery (Figure 2, page 3). Cells, monitored near the core of the battery (C10 and C16), generally had the highest recorded temperatures. Surrounded by other cells, less surface area was available for heat dissipation. Corner cells (C1, C6, C19 and C24) had lower recorded temperatures and cooled more quickly than the "core cells". For this study, core cell C10, judged to be worst case, was used for temperature rise measurement.

The correlation between battery cell (acid temperature) and case temperature was within 1°C for the majority of tests. See Figure 3 to Figure 10, page 7.

When discharged at the 6-hour rate (C/6, 120 A), cell temperatures generally rose slightly from the cold state and decreased slightly from the hot state. The mean rise for the cold discharge tests was 1.5°C, standard deviation (σ_{n-1}) = 1.6°C. For the hot discharge tests, the mean rise was -0.4°C, σ_{n-1} = 1.3°C.

A series of more severe discharge tests at double the 6-hour rate (C/3, 240 A) yielded a positive temperature rise of 5.0°C, σ_{n-1} = 0.5°C for cold discharge and 3.1°C, σ_{n-1} = 0.2°C for hot discharge.

The temperature rise during the charging tests was much higher. The results of these tests

Table II Charging Temperature Rise

Charger	Test* (H/C)	Mean Rise °C**	σ_{n-1} °C
1	H	12.5	0.3
	C	13.8	2.5
2	H	11.1	0.9
	C	11.5	2.4
3	H	12.0	3.0
	C	13.9	3.3
4	H	11.9	0.6
	C	11.7	1.8
5	H	9.7	0.5
	C	10.1	0.6
6	H	10.2	0.5
	C	12.1	1.5
7	H	11.6	2.6
	C	13.5	1.1
8	H	10.2	1.0
	C	12.0	2.4
ALL	H	11.2	1.7
	C	12.2	2.8

* - hot (H) or cold (C) charge test

** - rise above electrolyte temperature at start of test

along with the mean result for all tests are summarized in Table II.

Battery #3, a tubular plate model, was tested only with chargers 7 and 8 as it arrived late in the test program. The results of this limited testing could not be compared to the other batteries. Temperature rise and other measured results varied within the same limits of the other measured data. Therefore, all data was averaged for the temperature rise summary appearing in Table II.

Figure 3 to Figure 10, page 7 represent typical results for chargers 1 to 8. Case, acid and ambient temperatures are recorded versus time. Referring to Case and Acid temperatures, thermocouple locations on Battery 1 and Battery 2 (see Figure 2, page 3), were C1, C4 and C10, C13 respectively.

After charging, the battery cool-down rate in a room ambient temperature of 25°C was typically about 0 8°C per hour from an initial temperature of 37°C. Therefore, 4 hours after charging had completed, a battery would have cooled down about 3.2°C. Figure 11, page 8 illustrates the typical cool-down of a battery after charging. Cool-down is dependent on the difference in temperature between the battery and the ambient and how well the battery is insulated.

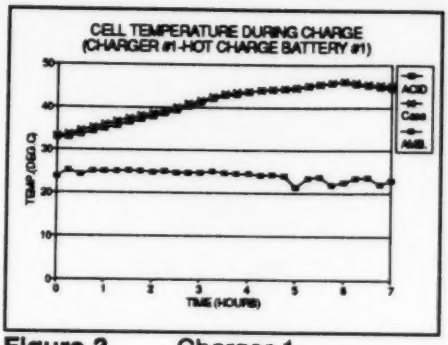

Figure 3 Charger 1

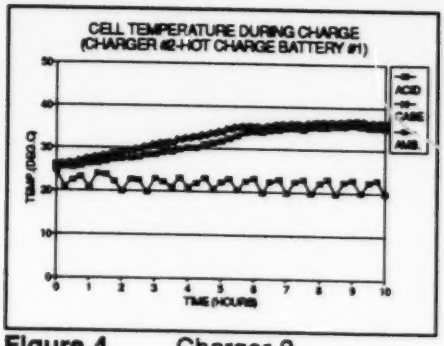

Figure 4 Charger 2

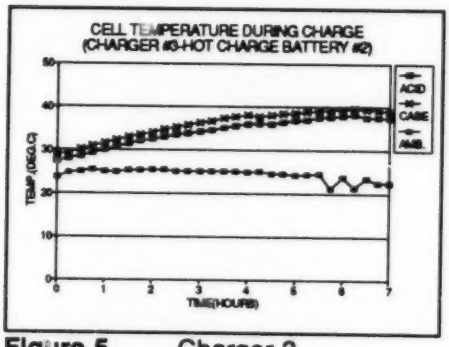

Figure 5 Charger 3

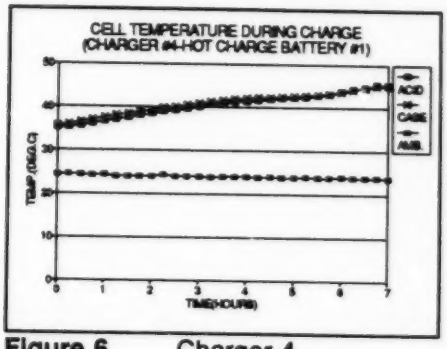

Figure 6 Charger 4

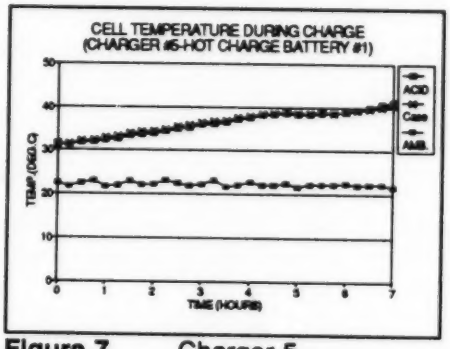

Figure 7 Charger 5

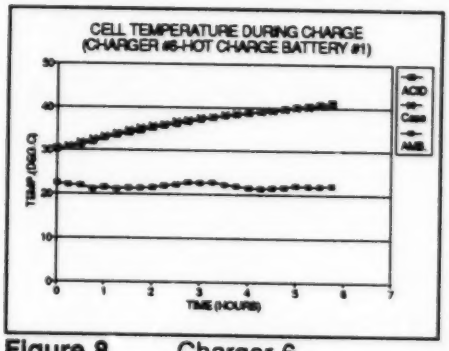

Figure 8 Charger 6

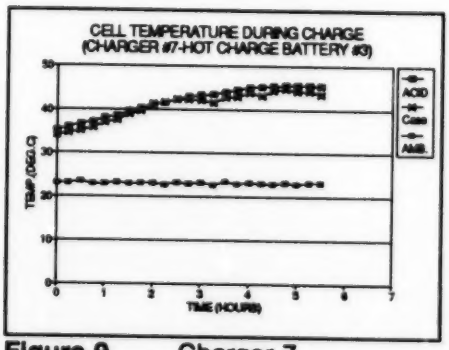

Figure 9 Charger 7

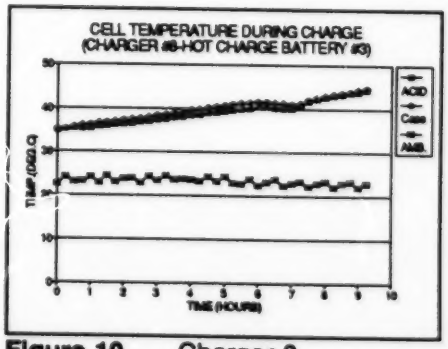

Figure 10 Charger 8

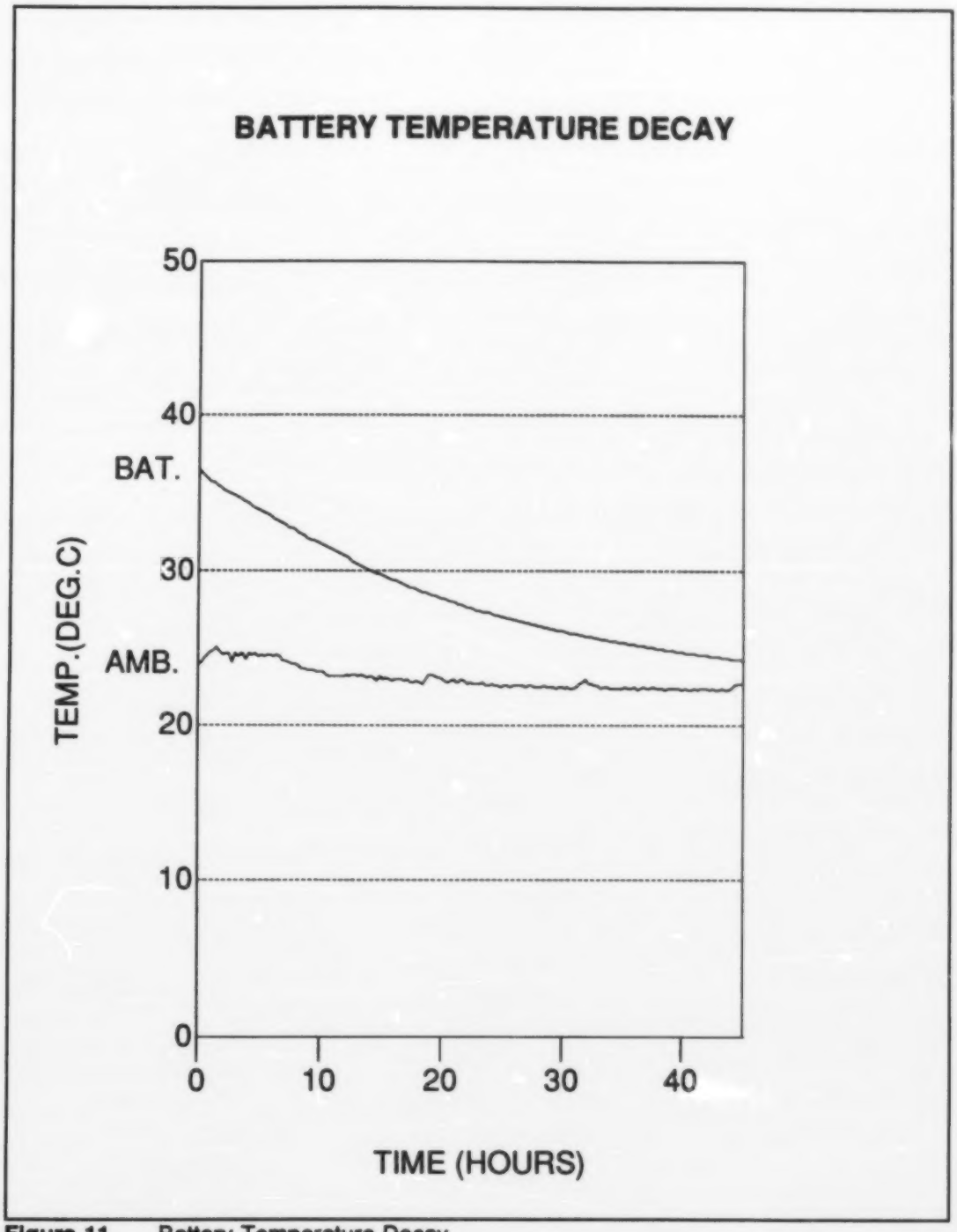

Figure 11 Battery Temperature Decay

3.2 Power Factor

Figure 12 to Figure 19, page 10 illustrate power factor and corresponding demands over the charging cycle for the chargers tested. Charger #1, a Thyristor type, exhibited the poorest power factor over the charging cycle at 0.65 compared to charger #4, a Switch-Mode type, which had a nearly unity power factor over the charging cycle.

Chargers 2 and 8, Magnetic-Amplifier types, also exhibited low power factors over the charging cycle. Charger 2's sharp decrease near the end of the charging cycle should not be considered a problem as the load is greatly diminished at this point. Charger 5, also a Magnetic-Amplifier, had a power factor of just over 0.8 for the entire charging cycle.

Chargers 3 and 7, Ferroresonant types, had similar power factor curves during the charging cycle; 0.8 at the beginning, rising slowly to 1 during the cycle. Charger 6, also Ferroresonant, had a higher initial power factor of 0.92.

If necessary (depending on the charger), power factor can be improved by installing capacitors across the line similar to induction motor power factor correction. Some charger manufacturers offer such power factor correction as an option.

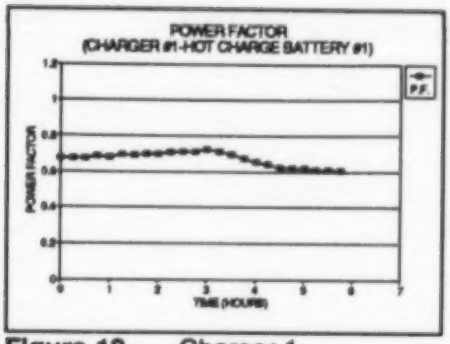

Figure 12 Charger 1

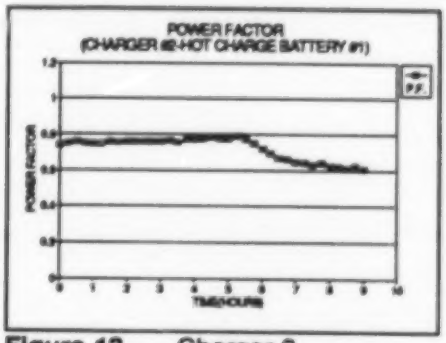

Figure 13 Charger 2

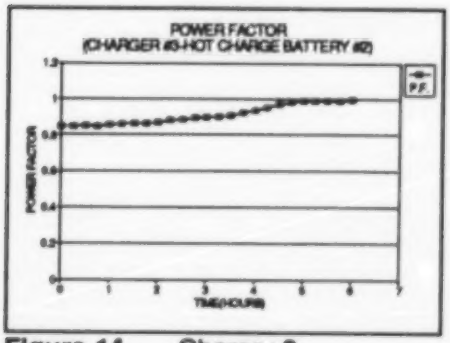

Figure 14 Charger 3

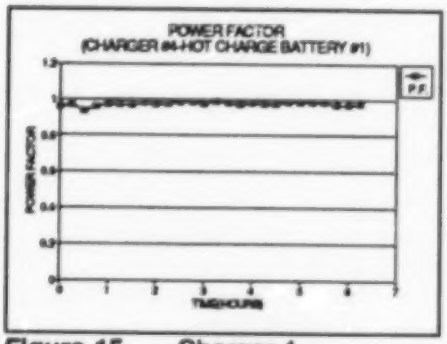

Figure 15 Charger 4

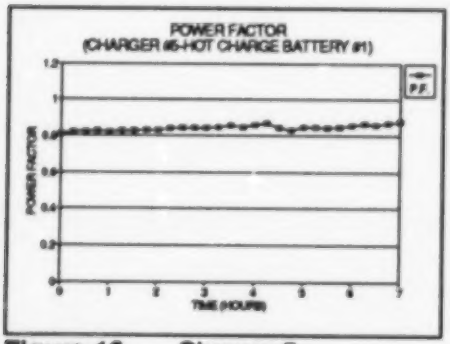

Figure 16 Charger 5

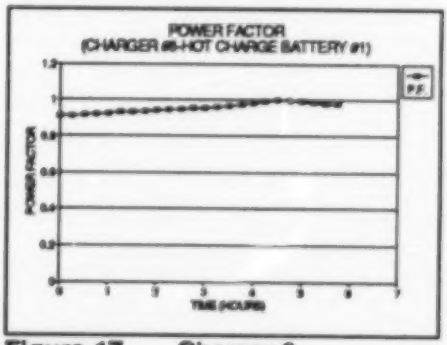

Figure 17 Charger 6

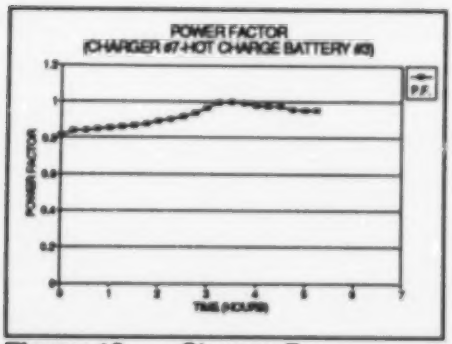

Figure 18 Charger 7

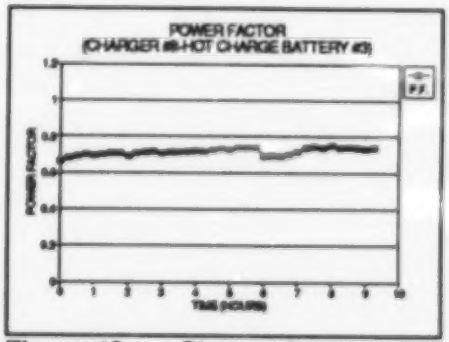

Figure 19 Charger 8

3.3 Charger Efficiency

Figure 20 to Figure 27, page 10 represent the ac to dc conversion efficiency during the charging cycle. Note that two efficiencies are plotted. Average efficiency is based on cumulative energy comparisons versus time while instantaneous efficiency is based on specific power comparisons. For many of the chargers, the instantaneous efficiency drops off significantly near the end of the charging cycle. However, this generally has little effect on average efficiency since demand is low at the end of the cycle.

Referring to Table III, average charger efficiencies ranged between 80.2 and 89%. The Switch-Mode sample had the highest efficiency, followed by Magnetic-Amplifier (Mag Amp), Thyristor and Ferroresonant types.

Table III AC - DC Charger Efficiency (Average)

Summary of Lift Truck Battery Charger Efficiency Tests		
Charger #	**Type**	**Average Efficiency (ac to dc) %**
1	Thyristor	83.3
2	Mag Amp	83.3
3	Ferroresonant	83.2
4	Switch-Mode	89
5	Mag Amp	87.7
6	Ferroresonant	83
7	Ferroresonant	80.2
8	Mag Amp	86.6

Total charge cycle efficiency (dc kWh out versus ac kWh in) includes the ability of the battery to store charge as well as the charger's ability to charge the battery adequately without overcharging. Rate of discharge and self discharge also affect this efficiency measurement. Table IV, page 12 summarizes total charge discharge efficiencies for each charger and battery tested.

Batteries 1 and 2 were the flat plate type of the same make and model. Most efficiency tests produced slightly higher overall efficiencies for battery 2 than battery 1. Battery 3, a tubular plate type, was not tested as extensively as the other two samples but yielded performance similar to battery 1.

Overall efficiency appeared to track average ac to dc charger efficiency within the limits of possible error. The effect of automatic "topping up", which periodically turns on the charger for brief periods to maintain the full charge of batteries left connected to chargers for longer than the initial charging period, was not included in this assessment. Such topping up would further lower the overall efficiency values.

The data was examined for correlation with charging temperature. No discernible differences could be found that could be attributed to battery temperature.

Table IV Charge / Discharge Efficiencies

Charger #	OVERALL EFFICIENCY (DISCHARGE dc kWh / CHARGE ac kWh)		
	Battery		
	#1	#2	#3
1	60.6	66.3	
2	62.7	65.0	
3	63.3	67.6	
4	66.2	72.7	
5	68.0	71.0	
6	61.6	66.5	
7	59.5		60.0
8	63.2		64.7

Charger Efficiency
(ac - dc)

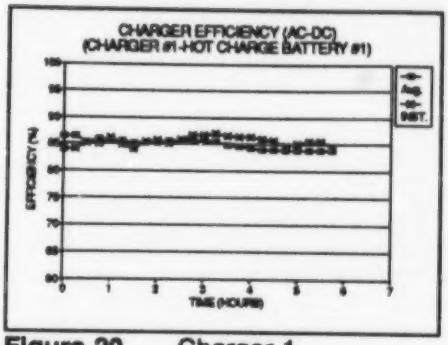

Figure 20 Charger 1

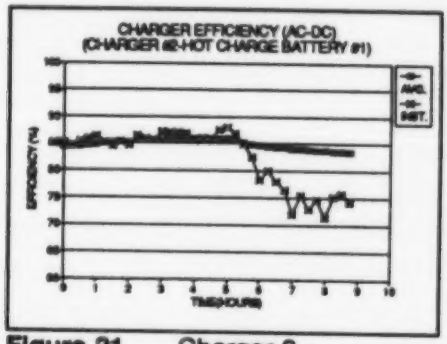

Figure 21 Charger 2

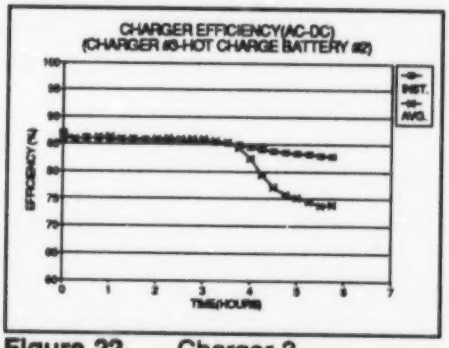

Figure 22 Charger 3

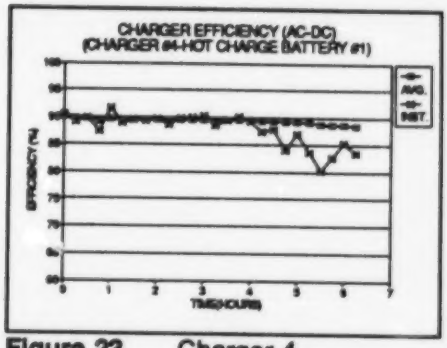

Figure 23 Charger 4

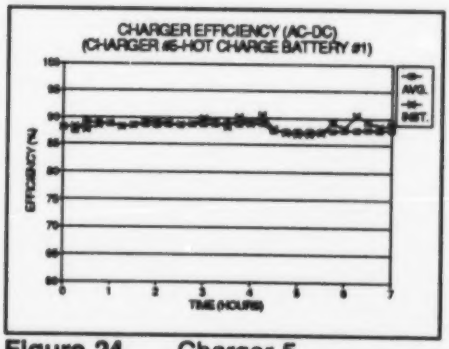

Figure 24 Charger 5

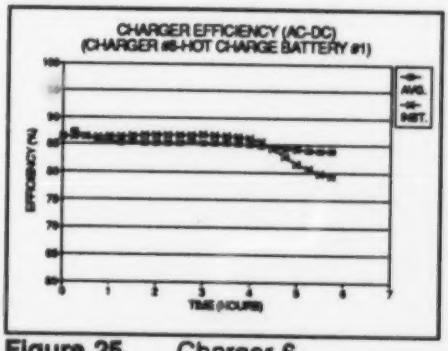

Figure 25 Charger 6

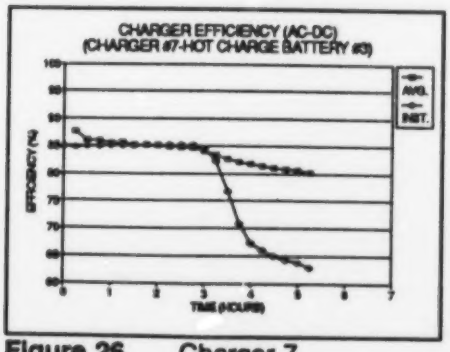

Figure 26 Charger 7

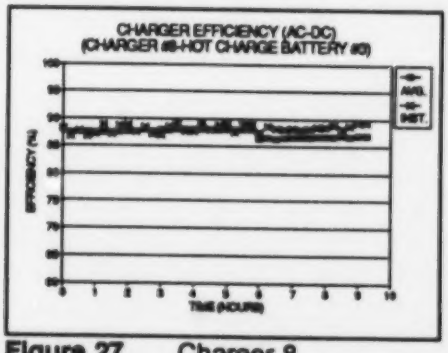

Figure 27 Charger 8

3.4 Demand

Figure 28 to Figure 35, page 15 represent the demand for the eight chargers both in terms of kW and kVar. Note that chargers #2 and #8 (Magnetic-Amplifier) had lower demands, while the charging time is significantly longer than the other chargers. Charger 5, also a Magnetic-Amplifier type, had a higher demand, permitting it to charge the battery completely within 7 hours.

Chargers with higher demands recharged the batteries in about 6 hours. The initial high demand (9 - 10 kW) dropped quickly to a lower rate (2- 3 kW) for the duration of the charge.

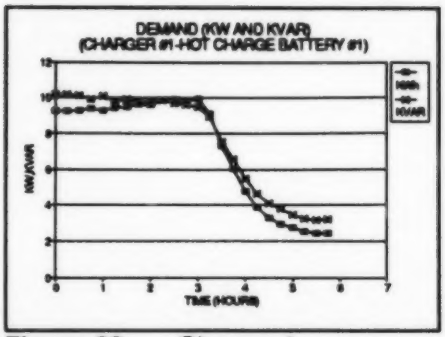

Figure 28 Charger 1

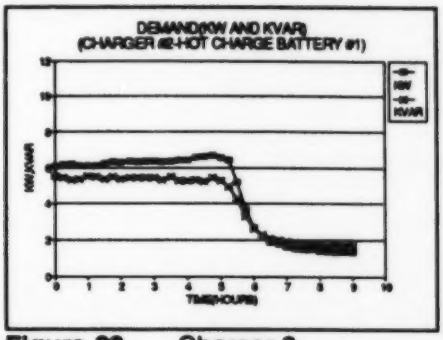

Figure 29 Charger 2

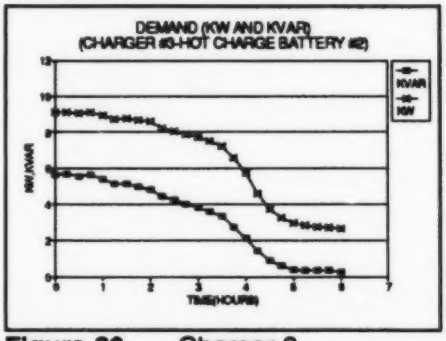

Figure 30 Charger 3

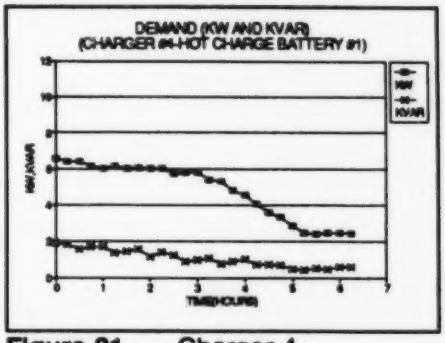

Figure 31 Charger 4

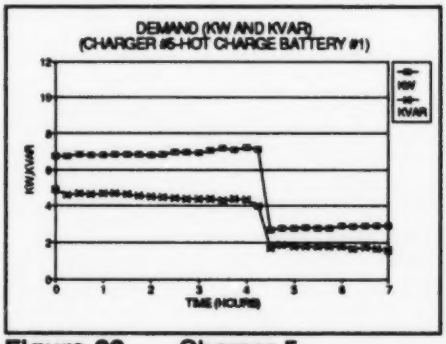

Figure 32 Charger 5

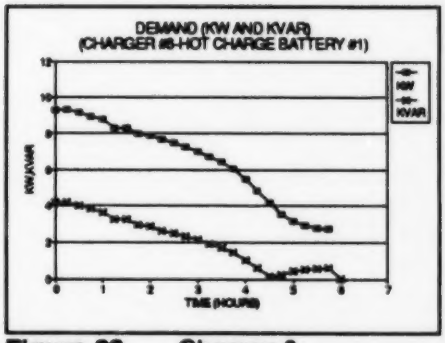

Figure 33 Charger 6

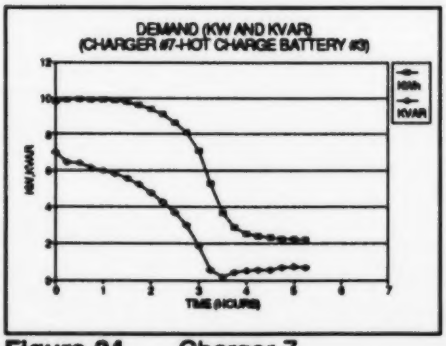

Figure 34 Charger 7

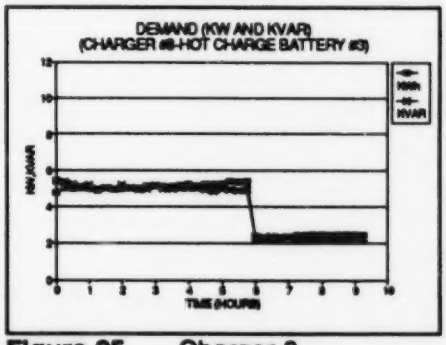

Figure 35 Charger 8

3.5 Amp-hour Charging and Discharging Profiles

Figure 36 to Figure 43, page 17 illustrate the amp-hour charging profiles superimposed with discharging profiles for the eight chargers. Note that the discharge profile is independent of the charger used.

Amp Hours
(Charging and Discharging)

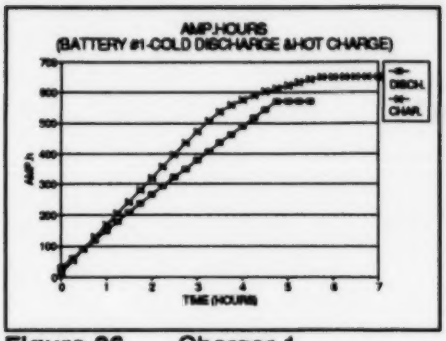

Figure 36 Charger 1

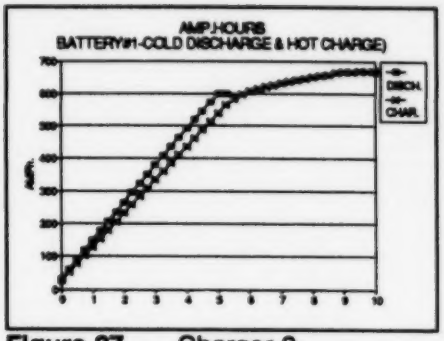

Figure 37 Charger 2

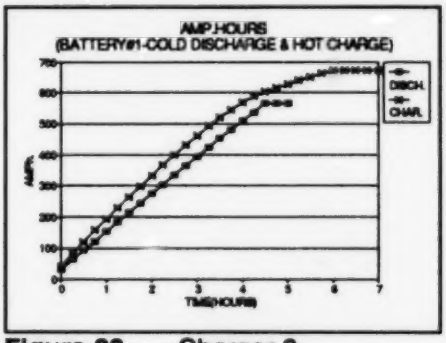

Figure 38 Charger 3

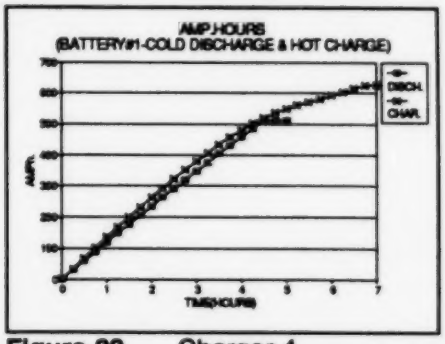

Figure 39 Charger 4

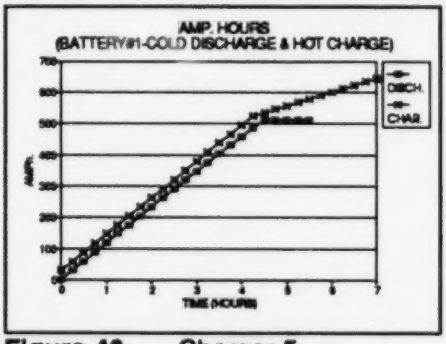

Figure 40 Charger 5

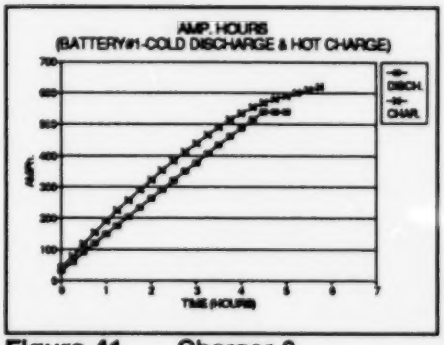

Figure 41 Charger 6

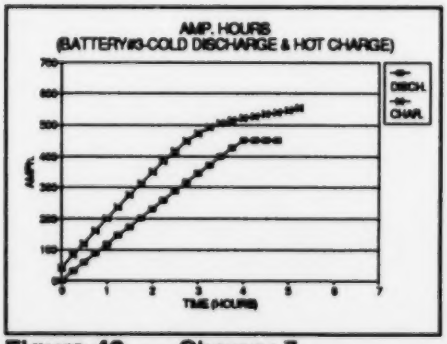

Figure 42 Charger 7

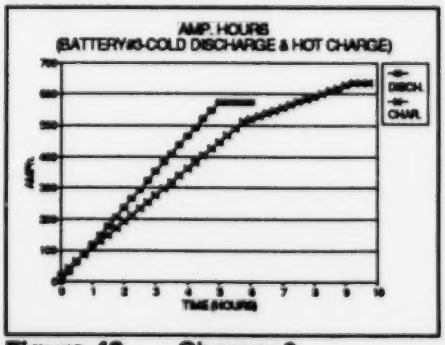

Figure 43 Charger 8

3.6 Harmonic Tests

The following is a summary the conclusions and recommendations based on the results of tests performed by the System Studies Section of Ontario Hydro Research Division[4].

Charger harmonic currents varied among the chargers tested. Current distortion is a good indicator of the harmonic performance of battery chargers. However, when expressed as a percent total harmonic distortion (THD%), reference should be made to the RMS base current. For example, a high THD% is less significant when the load current is small (eg the end of a charging cycle or one or two chargers connected to a feeder) than when the load current is large (eg the beginning of a charging cycle or many chargers connected to the same feeder).

Even though the effect on the voltage waveform was minimal, it was concluded such a measurement was not a good indicator of the harmonic performance of battery chargers. This can be attributed to the fact that harmonic distortion of the voltage waveform is a function of the ac supply impedance and the harmonic conditions.

The harmonic performance of the battery chargers depended on the type of design. The Ferroresonant chargers had the lowest harmonic current distortion. The other three types tested showed similar performance to one another because the incoming ac current is switched or rectified.

There are no standards that can be used to accept or reject products based on harmonic performance. Nevertheless, the test results can be used to make informed decisions on the selection and application of industrial battery chargers in order to minimize the impact of the injected harmonic currents on other equipment and on the quality of the utility supply system. Good judgement may also avoid the need to install additional mitigative equipment to resolve problems (eg.line conditioners or filters).

---

[4] The results for chargers 1 to 4 are documented in OHRD Report 90-47-H "*Harmonic Currents for Industrial Battery Chargers*" by G.K. Hatanaka. The results for chargers 5 to 8 plus an overview of chargers 1 to 8 are documented in OHRD Report 90-324-K "*Harmonic Currents From Industrial Battery Chargers - Addendum*" by G.K. Hatanaka.

4 Discussion

Many factors affect battery life. One is temperature. Bode[5] observed that operational life increases with rising temperature in the working range between 35 and 45°C by not less than 25 cycles/°C. Above 45°C the negative plate limits the life because of capacity losses through sludge formation. Battery manufacturers and distributors[6] advised against exceeding core temperatures ranging between 46°C and 49°C (depending on the manufacturer surveyed). Therefore, assuming the lab results are typical, the user should avoid initiating a full charge when the cell temperatures are above 35°C. Less than a full charge would permit initial temperatures higher than 35°C as long as the final temperature does not exceed manufacturer's recommendations.

Since the batteries were discharged to 1.72 V/cell, a very deep discharge, charging requirements for the tests conducted should be considered as worst case. In practice, the lift truck battery would not be discharged to the same degree and should therefore result in lower temperature rise during charging.

Referring to the temperature rise results listed in Table II, page 5, mean rise temperatures were up to 2°C higher for charging from the "cold state" than from a "hot state", ignoring the standard deviations for the two populations. Comparing this information to Figure 11, page 8 "Battery Temperature Decay", the absolute difference in overall temperature rise between charging immediately and after waiting 4 hours is 1.2°C. If the standard deviations are taken into account, the overlap of results suggests the gap may be even smaller. As well, cool down of the batteries was not impeded as the tests were conducted in free air with good ventilation. In these tests, allowing the battery to cool down four hours after charging did not significantly reduce the temperature (Figure 11, page 8). It is suspected that batteries charged in lift trucks would cool down even more slowly. (Field testing would be required to confirm this.)

The correlation between battery cell and case temperature was within 1°C for the majority of tests. Field monitoring, of lift truck battery temperature, using battery case temperature as a reference should provide sufficient accuracy. Note that probes placed between inner cell casings (as opposed to the outside battery surface) provided the best correlation.

The tests conducted for this project were carried out under controlled laboratory conditions. Since one size of battery was tested (720 A.h), the results may not be truly representative of all lift truck batteries and chargers. The results obtained in this study do serve as a useful bench mark against which other measurements can be compared.

The Switch-Mode charger (Sample 4) exhibited the best overall performance. This finding may

---

[5] Bode, Hans *Lead-Acid Batteries* Translated by R.J. Brodd & Karl V. Kordesch, John Wiley & Sons, Inc. 1977, ISBN 0-471-08455-7

[6] Telephone survey of battery manufacturers and distributors, November 1989.

or may not hold true for all chargers of this type. It would be useful to study charger types and categorize their component losses. This knowledge would be useful for informing customers of the merits of charger types. As well, it may be possible to design and demonstrate a more efficient charger design.

Chargers with high demand were capable of fully charging a battery in less than seven hours. Charger 4 had a significantly lower demand but was still capable of charging within the same time constraint. Chargers 2 and 10, both Magnetic-Amplifier types, also had lower demand but took more than 9 hours to charge the battery. The latter types may be less desirable for off-peak charging purposes if the battery is needed before 8:00 AM. Use of a timer to turn the charger off as well as on may be a possible solution to ensure the charger is off during the peak.

In general, solid state switching types (Thyristor, Switch-Mode, Magnetic-Amplifier) exhibited greater voltage waveform distortion than the Ferroresonant types tested. Power quality standards are needed to assess the impact of harmonic current injection.

5 Conclusions and Recommendations

Battery temperatures increase more significantly during charging than during discharging. Based on the test results obtained in this study, battery cell temperatures should be less than 35°C before initiating a full charge. Batteries charged once in a 24-hour period should not experience any difficulty in meeting this stipulation. Waiting four hours after charging did not produce significant cool-down in the laboratory measurements (Figure 11, page 8).

Thermocouples inserted in the space between inner cell cases provided good correlation with actual electrolyte temperatures. This would facilitate installation of alarms or control devices to prevent over temperature from occurring during charging.

Overall, Charger 4, a Switch-Mode model, provided the best performance. It had the highest ac to dc efficiency (89 - 90%) and also had the best power factor (almost unity). Demand was also significantly lower than many other chargers while still permitting a full charge in less than 7 hours. Only the Ferroresonant chargers surpassed the Switch-Mode Model in terms of lower waveform distortion.

Chargers requiring more than 8 hours to fully charge a battery may not be suitable for an off-peak charging program if the battery is needed before 8:00 AM.

The Ferroresonant charger was clearly superior to the other design types in terms of harmonic performance. However, there are presently no standards or benchmarks that can be used to accept or reject products based on harmonic performance.

Further testing may be warranted to determine the effect of off-peak charging on older batteries and monitoring of lift truck batteries in the field.

6 Acknowledgements

We wish to acknowledge the following:

Technician: Mr. A. Goldenberg for his assistance in conducting the laboratory testing and graphic preparation.

System Studies: Mr. G.K. Hatanaka and Mr. B. Pietrantonio for harmonic analysis.

Students: Mr. P. Frontczak, Sheridan College and
Mr. C. O'Brien, Memorial University.

Approved:

A.F. Baljet
Manager
Electrical Research Dept.

Submitted:

C.E. Keyes
Utilization Engineer
Utilization Section

APPENDIX

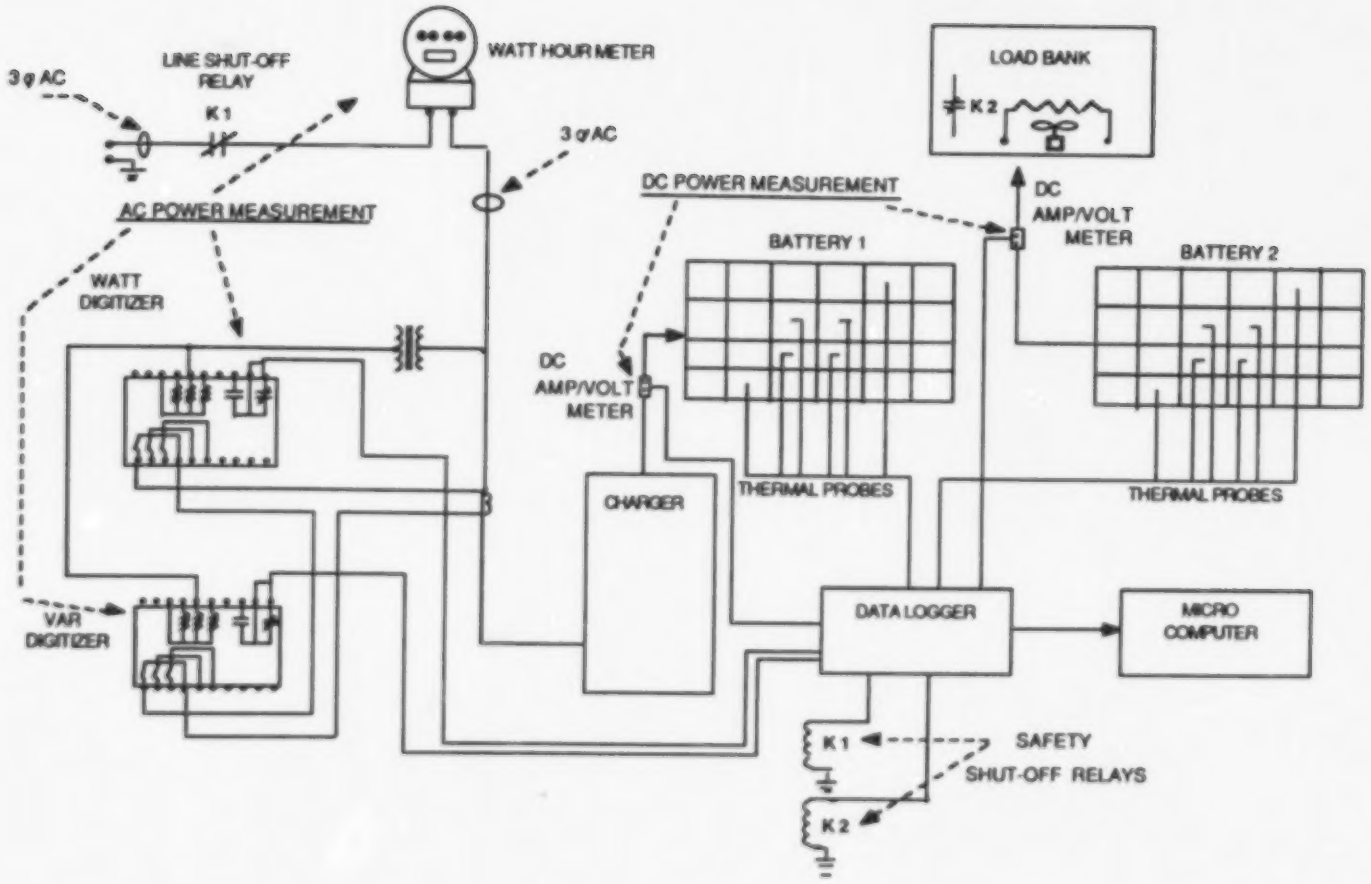

Figure A-1 Equipment and Wiring Schematic

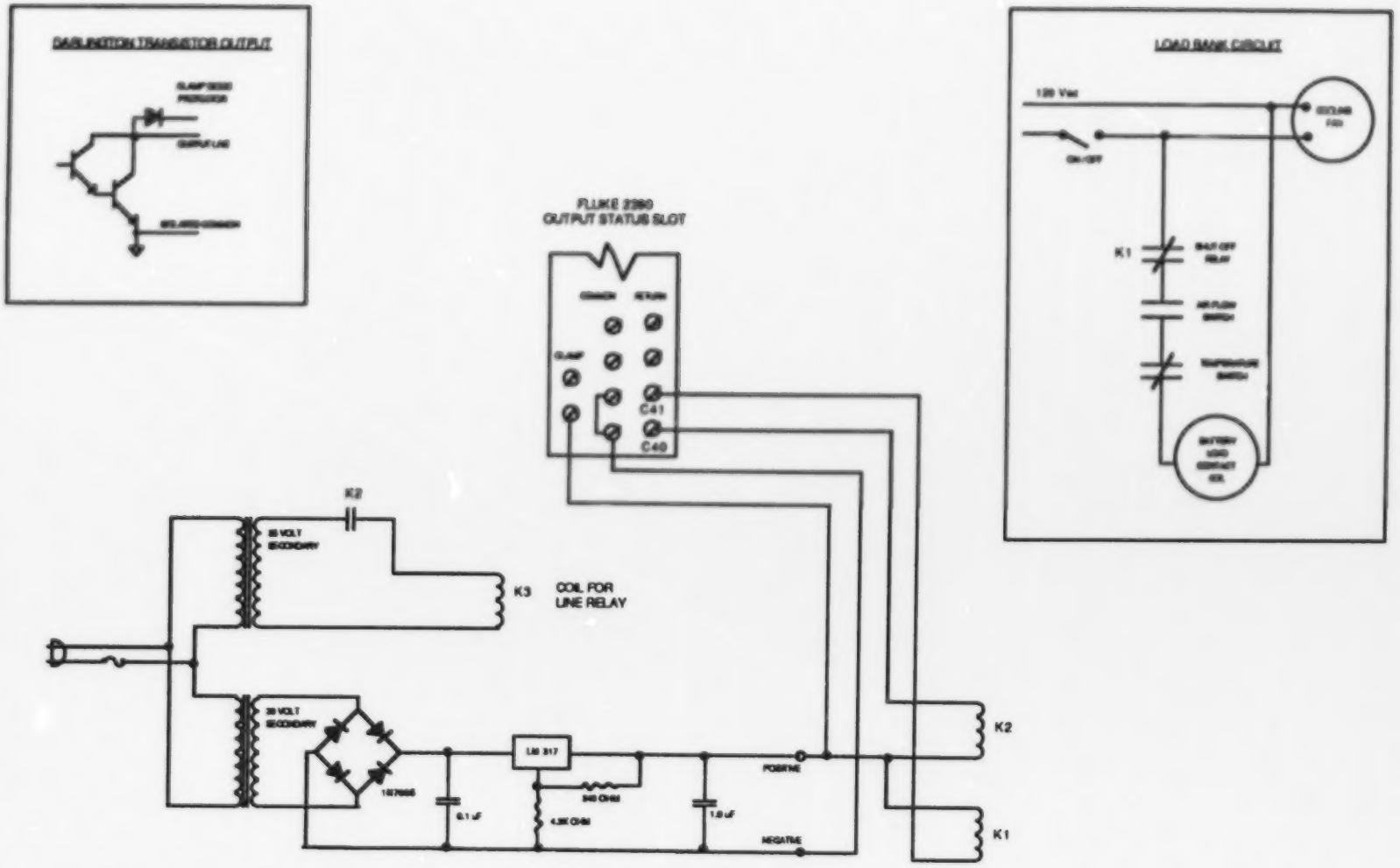

Figure A-2 Detail of Safety Shut-Off System

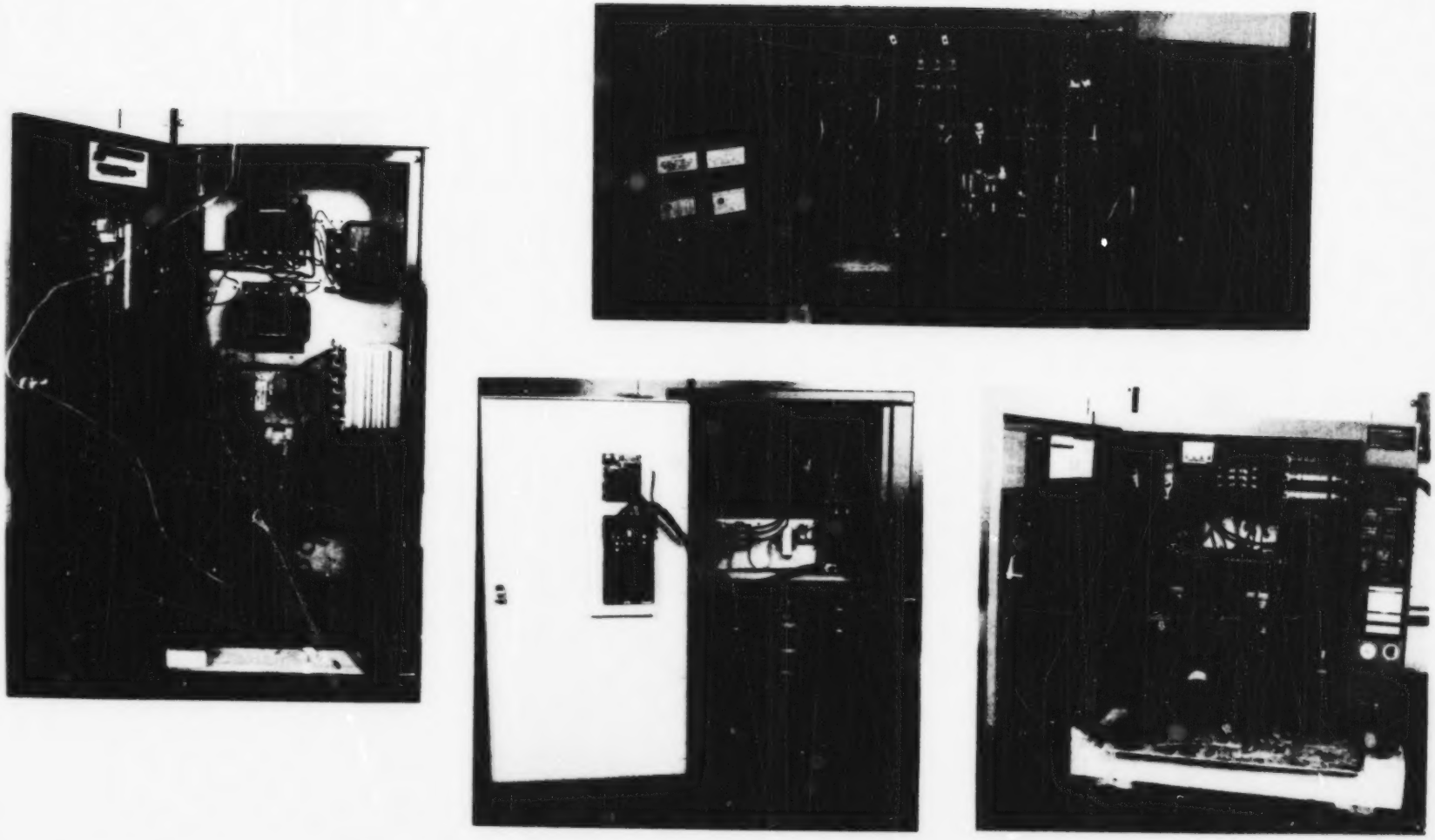

Figure A-3 Examples of Chargers Tested

Figure A-4 Batteries Tested